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Techno-economic analysis of a Solid Oxide Fuel Cell installation in a biogas plant fed by agricultural residues and comparison with alternative biogas exploitation paths

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Abstract

In this work, the comparison between three biogas exploitation paths is analyzed from both an energetic and economic point of view. As main current available Combined Heat and Power (CHP) options, a traditional Internal Combustion Engine (ICE) and a Solid Oxide Fuel Cell (SOFC) are compared. Furthermore, biogas upgrading (UPG) is analyzed as a discussed and innovative alternative to electrical production.

Currently, main issues related to the agricultural biomass plants can be addressed to: the reduced subsidies for the electrical production, especially in case of energy crops feeding, the wasted thermal energy, which usually cannot find a user in the surroundings and the emissions from traditional Internal Combustion Engines (ICEs), which usually exceed limits and require the use of a post-combustor.

The analysis has been applied to a typical biogas plant fed with agricultural residues in Piedmont. Data on current biogas production, methane content and auxiliaries consumption have been collected. Electrical and thermal load for the plant have also been analyzed, in order to calculate the net efficiency of the system.

Results show positive effects of the SOFC system from an energy point of view with respect to traditional systems. The advantages in terms of electrical production and low maintenance costs are able to generate a higher incomes on a yearly basis, even if the high investment costs still generates, in the current scenario, a higher PayBack Time (PBT). Analyzing a future scenario with target fuel cell costs, which have been almost reached in countries where the market is grown (e.g. USA and Asia), the investment reaches interesting economic benefits even if compared to traditional systems.

The bio-methane choice analyzed shows an interesting investment cost but with lower net yearly incomes which cumulatively generates a slow investment recovery time in the current scenario.

Peer-review under responsibility of the Scientific Committee of ATI 2016.

Keywords: Biogas, Engine, Fuel Cell, Agricultural Biomass;

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1. Introduction

The presented work focuses on the comparison of three biogas exploitation paths from an energetic and business point of view. A similar work has been performed by [1], where the same scenarios are compared: despite the same starting point, the present work aims to achieve real performances by using data from a real small size biogas plant and real components operation. A life cycle analysis of the same competitive scenarios has been also evaluated in [2]. Biogas is a widely discussed topics [3][4] and biogas upgrading is an emerging process which, through different possible reactions, lead to the production of a biological methane flow, which could either be sent to the grid or used for transportation [5][6]. Different supporting schemes are also available according to the chosen biogas exploitation path. Thus, the following analysis aims to compare the most discussed and promising biogas utilization technologies both from an energetic and economic point of view.

2. Plant description

The analyzed plant is a medium size farm located in Tetti Rolle, a small village in the Torino premises. The farm core business is related to the production of milk, then sold to the industry (around 280 cows are raised there). On December 2012 the farm owner has installed a biogas production plant, fed by locally produced biomass from animals and crops. In particular, a thermophilic anaerobic digester has been installed and fed by livestock effluents (collected partially with and partially without straw) and a portion of energy crops (mainly corn) to increase the overall biogas yield production.

On a daily basis, the owner of the farm introduces in the digester 2 tons of livestock effluents (collected with straw) and 1 ton of corn silage. Furthermore, 15 m^3/d of effluents (liquid, without straw) are also fed through an automatic pumping system. From the anaerobic digester, biogas and digested biomass are produced: the first is cleaned and sent to a cogeneration system, the second is stored in an open tank and re-used as a fertilizer in the farm fields (used for the cow meal production). No biogas storage system is installed and then the gas is only stored in the digester upper part and instantaneously sent to the engine.

Biogas, before feeding the ICE, is sent to a blower and to a chiller, to avoid water condensation, and to a sulphur removal system. In the current layout, no media is used in the sulphur removal reactor. The ICE produces electricity, which is firstly used for the auxiliaries consumption (chiller, blower and pumps) and then sold to the grid, and heat in form of hot water, used for the digester heating system. The anaerobic digester is equipped with internal circular pipes, filled with hot demineralized water, in order to keep the internal temperature as stable as possible.

The plant is included in the first "*Tariffa omnicomprensiva*" system, defined by D.M. 18/12/2008 and ended on December 2012, according to which the electricity produced by similar biogas plants is paid 28 c€/kWh. Since the current subsidy scheme is now changed with a reduced price for the electricity sold to the grid, and because of the more restrictive laws on emissions to atmosphere are not always accomplished by standard ICEs, a technical and economic proposal has been developed for the presented plant. The scope is to provide an evaluation of different scenarios, applicable to the analyzed farm and to all similar scenarios.

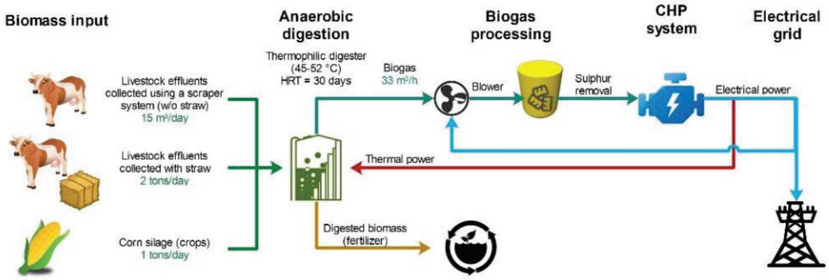

Figure 1. Plant current layout.

3. Case studies

3.1. Current scenario - biogas fed to an ICE

The current plant layout has been already presented in Chapter 2.

Due to the decision of the farm owner to work in manual mode, without almost any control loop and set point, no data logging or performance analysis are obtained from the plant. For this reason, the techno-economic evaluation is performed on the installed ICE nominal efficiency and cost, and final considerations are presented in order to understand the real performance of the plant.

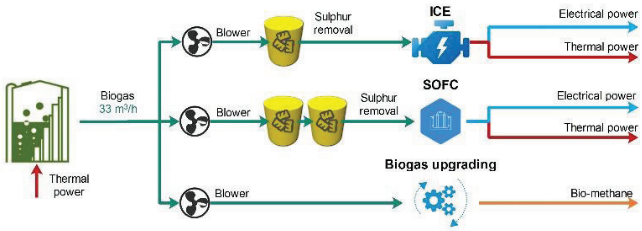

Figure 2. Case study layout.

3.2. Future innovative scenario – biogas fed to an SOFC

The first proposed alternative scenario is related to the installation of a fuel cell based cogeneration system, by installing a SOFC module. The reason for the use of an SOFC system are mainly related to the following aspects:

- ICEs shows reduced electrical efficiencies (~ 38%) for low size systems (<100 kW) while SOFC modules, being modular systems, are able to guarantee a constant efficiency also at low system sizes (53%). A higher electrical production per unit of biogas produced is translated in higher incomes during plant lifetime.
- SOFC modules can work in a modulation range of 100-50% thus enabling the system to run, with almost stable performance, even when a variable biogas flow rate is produced. This is a typical problem in small size plant where no gas storage is installed.
- ICEs currently show criticalities for what concerns emissions to atmosphere, and many plants have already installed a post-combustion system to reduce the amount of NOx and organic compounds. Electrochemical systems, such as SOFC, produce nearly zero emissions.
- On the contrary, being in their early stage in the market, main criticalities related to fuel cells are the investment costs and the low tolerance to contaminants. The first could be reduced by national funding for "clean" energy production and with an increased introduction of such systems in the market. The second point can be solved by a detailed design of the cleaning system and an online contaminants measurement.

The analyzed scenario will consider the installation of a SOFC module, fed by the same biogas flow rate available in the farm now, together with a clean-up system able to remove harmful contaminants up to safety level for the fuel cell (usually lower than 50 ppb).

3.3. Future innovative scenario – biogas upgrading to bio-methane (UPG)

The second proposed scenario refers to an alternative solution with respect to the exploitation of the biogas for the production of electricity and heat. In fact, in this case study, the biogas will be upgraded to produce bio-methane sold to the gas grid. Due to the reduced subsidies on electrical production from biogas in December 2012 (from 28 to a maximum of 24 c€/kWh) and the new supporting scheme for biogas upgrading, this scenario has become an attractive solution for existing and new biogas plants.

The configuration of the new plant will differ from the previously two described, because of the presence of a system for the upgrade of the biogas. The target of the upgrade process is to obtain a final gas (bio-methane) with a percentage of CH_4 in the range of 95-97 % and only a residual percentage of CO_2 [7]. The bio-methane quality is defined by the UNI/TR 11537:2014.

Among all the existing methods for the biogas upgrade, in this work it has been chosen the *Pressurized Water Scrubbing (PWS)* method. The method is very simple and consists in the passage counter-current of a water flux and the biogas flux inside an absorption column. The water will absorb the major part of CO_2 while the output gas will be almost totally composed by CH_4. After this step, the gas has to be dried and then it can be sold to the grid or used. The process has to be operated at high pressures (generally between 7 to 10 bar) in order to facilitate the absorption of carbon dioxide.

The choice of this method can be addressed to the following advantages:

- it is a simple method that allow to obtain very low losses of methane during the process (lower than 0.8%) without the use of chemicals;
- it is possible to remove also biogas contaminants, as H_2S and NH_3, if at low concentrations;
- currently is the most used technique for the production of bio-methane.

4. Methodology

4.1. Validation of biogas yield

The biogas production declared by the plant owner has been compared using literature data referring both to biomass composition and biogas yields for sources involved in the process studied.

First of all, the total amount of daily biomass available to be used as input for the anaerobic digestion process were determined. In particular, not the entire biomass has been considered for the production of biogas, but only the percentage defined as Volatile Suspended Solids (VSS), calculated as:

$$\mathrm{VSS} = \mathrm{vss\%} \cdot \mathrm{TSS} \tag{1}$$

$$\mathrm{TSS} = \mathrm{tss\%} \cdot \mathrm{TB} \tag{2}$$

where:

- TB are the tons of Total Biomass used as an input for the digester,
- TSS are the tons of Total Suspended Solids contained in TB,
- vss% and tss% are respectively the percentage of VSS in TSS and of TSS in TB.

The next step was the calculation of the daily biogas production (DBg) using equation (3) and considering that each kind of biomass involved is characterized by a proper biogas **yield** (shown in Table 1). Dividing by 24 hours the value of DB_g, it is finally possible to obtain the hourly biogas production.

$$\mathrm{DBg} = \mathbf{yield} \cdot \mathrm{VSS} \tag{3}$$

Table 1. Parameters referring to the different types of biomass considered .

Biomass parameters	Bovine effluent (without straw)	Bovine manure (with straw)	Corn silage	Straw
TSS (% on TB base) - [9] [10] [11] [12]	8.2	21	34.6	88.3
VSS (% on TSS base) - [9] [10] [11] [12]	73	79	95.2	93.7
Biogas yield (Nm^3/t_{VSS}) - [13]	375	425	650	375

4.2. Plant design

For case study 1 and 2, the size of the CHP system has been determined starting from the biogas flow rate and the related methane percentage (54-59% CH_4). As will be seen, referring to the current scenario, the theoretical power production will be higher than the real one, probably because of system inefficiency mainly attributed to the sulphur not removed or ICEs working not at full load because of gas fluctuations. Electrical and thermal production can thus be determined, together with declared emissions from system producers. All auxiliaries consumption have been considered included inside the CHP efficiencies, except for the biogas compressor, which consumption has been determined through a simple model in Aspen Plus® (isoentropic compressor, η_{is}=90%, η_m=80%).

For case study on biogas upgrading, a PWS model available in [7] has been used to determine the system efficiency and auxiliaries consumption. The bio-methane production has been assumed as the 100% methane fraction (equal to 56.5%, mean value from real plant) since in [7] it is demonstrated that, through PWS, methane losses can be kept to less than 1%.

After sizing the main energy production system for the scenarios, the clean-up system was designed in order to guarantee the required purity levels. The input H_2S concentration has been assumed equal to 400 ppm, as declared by the plant owner. The required outlet values, shown on Table 2, are 150 ppm for the ICE case study, as found on the engine datasheet and 0 ppm for the SOFC. For the bio-methane, since scrubbing is already performed inside the system, sulphur is considered to be removed here to allowable levels for grid. From the knowledge of the H_2S to be removed, the flow rate and the replacement time (assumed 6 months for all cases), the catalyst required charge can be determined as:

$$Q_{AC} = c_{H_2S} \cdot \dot{m}_{bio} \cdot t_r \cdot SF \quad (4)$$

Where:

- Q_{AC} is the required catalyst amount per charge [kg]
- c_{H_2S} is the hydrogen sulfide concentration in ppm to be removed, determined as the difference between inlet and outlet values [ppm]
- $\dot{m}_{bio}$ is the biogas flow rate [kg/s]
- t_r is the chosen replacement time [s]
- SF is the Safety Factor, assumed equal to 3

Table 2. System design and dimensioning.

Parameter	Unit	Reference	Scenario 1	Scenario 2	Scenario 3
Biogas flow rate	m^3/h	Data from real plant	33	33	33
Electrical efficiency	%	SOFC [14] ICE [15]	38.0%	53.0%	-
Thermal efficiency	%	SOFC [14] ICE [15]	29.1%	27.0%	-
Electrical power production	kW		65.69	91.65	-
Auxiliaries consumption	kW	UPG [7]	2.07	2.07	8.25
Net power production			63.63	89.59	-
Thermal power production	kW		62.3	57.9	-
PWS efficiency	%	UPG [7]	-	-	89.8
Bio-methane production	m^3/h		-	-	18.6
Inlet H_2S concentration	ppm	Data from real plant	400	400	-
Required outlet H_2S conc.	ppm	SOFC [16] ICE [15]	150	0	-
AC adsorption capacity	mg H_2S / g AC	[17]	100	100	-
AC replacement time	months	HP	6	6	-
AC real quantity	kg		5.49	8.78	-

4.3. Energy analysis

For the energetic and economic analysis a control volume is also required to carry on the performance evaluation: for both cases, the control volume start from the raw biogas exiting the digester (since this component is included in all the scenarios) and includes all the units until the energy release to the external (electrical or NG grid). No internal energy recovery has been considered since, from an economic point of view, it is more convenient to sell all the produced energy to the grid and re-buy the required amount for internal consumptions.

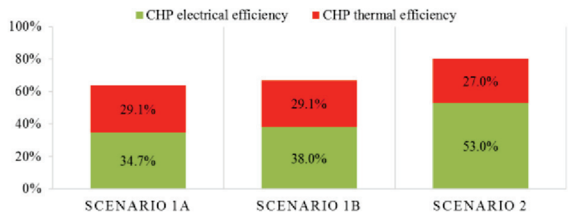

Figure 3. Efficiency comparison among scenarios 1 and 2.

On Figure 3 the efficiency of the two CHP scenarios (1B and 2) is compared: furthermore, starting from the declared electrical production in the system, the electrical efficiency of the real plant (Scenario 1A) has been determined. As can be seen, in the real case a value more than 3% lower is shown: as discussed before, this trend could be due to the poor ordinary maintenance on the hydrogen sulfide removal system and the ICE, which leads to system malfunctioning and performance losses.

4.4. Economic analysis

The economic evaluation of the three business cases starts from the definition of the core costs components:

- Investment costs, due to the year 0, year of construction, for the purchasing and installation of the system
- Operating costs, due every year from year 1 to end of life (N, assumed 20 y).
- Operating incomes, related to subsidies and supporting schemes in Italy.

For each scenario the three cost components have been determined.

Scenario 1: ICE

The internal combustion engine capital cost has been derived from a real specific cost in €/kW for different sizes (1 MW and 200 kW), re-scaled linearly to the real system. The final chosen value is thus 1’500 €/kWe. For the clean-up system, since commercial systems are already available for ICE target requirements, the target cost from [18] has been taken into account (200 €/kWe). The operating expenditures are the sum of the ICE ordinary maintenance (1.65 €/working hours, [15]) and clean-up maintenance (two replacements per year of the determined catalyst amount, which cost has been assumed as 5 €/kg, from a commercial offer on sulphur AC).

For what concerns the two CHP scenario, the incomes are related to the subsidy for the electricity sold to the grid according to [19]. In particular, for biogas derived from sub-products of biological origin (like livestock effluents), and plant sizes lower than 300 kWe, the available base subsidy is equal to 23.6 c€/kWh. The analyzed system is not suitable for any extra-subsidy request, as it is foreseen in case of high efficiency cogeneration and nitrogen recovery.

The plant capacity factor has been determined considering 2 hours per week of stop (because of lubricating oil change) plus one week per year for longer maintenance.

Scenario 2: SOFC

For the SOFC system, capital expenditure includes the SOFC module investment cost (determined from internal exchange with FC producers: both 3’000 €/kWe and 5’000 €/kWe case studies have been analyzed) and the clean-up system (cost assumed 1’000 €/kWe from [18]).

For what concerns operation expenditures, on a yearly basis, only the AC replacement has been considered (same costs as for ICE), since the SOFC stack replacement occurs every 5 years and the total amount is equal to 30% of the initial investment ([20]). The subsidy scheme is the same as for the ICE case study.

The capacity factor of the plant has been determined considering 1 week of stop per year.

Table 3. CAPEX and OPEX evaluation.

Parameter	Unit	Value
Scenario 1		
Clean-up system	€	13’139
ICE system	€	102’000
Clean-up maintenance (AC substitution)	€/y	54.89
ICE maintenance	€/y	14’005
Incomes	€/y	82’213
CF	%	96.9
Scenario 2		
Clean-up system	€	91’654
SOFC system	€	458’271 – 274’962
Clean-up maintenance (AC substitution)	€/y	87.82
SOFC maintenance	€/5y	164’977
Incomes	€/y	106’121
CF	%	98.1
Scenario 3		
Biogas upgrading system	€	143’766
Upgrading maintenance	€/y	32’135
NG for digester heating	€/y	18’865
Incomes	€/y	63’938
CF	%	98.2

Scenario 3: UPG

The upgrading system investment and operation cost have been determined from [7], by scaling specific consumption values and costs on the biogas volume flow rate. Since in case of biogas upgrading no heat is available from the process, thermal power should be supplied to the digester to keep the entire volume in mesophilic condition. In order to take into account the required heat, the operating cost for NG from the grid has been taken into account, by considering a 95% efficiency boiler and a NG price for industrial users (in the range 26'000-263'000 m^3/y) equal to around 50 c€/Sm^3 (determined from 2014 values from Italian Authority for Electricity and Gas, rescaled to 2016 according to available trends from the same website). The required thermal load for the digester has been considered as 50 kW, equal to the current thermal production from the ICE in the plant, which is sufficient to heat up the volume all the year.

For what concerns incomes, the DM 5/12/2013 defines the guidelines for the subsidizing of bio-methane production. Depending on the layout of the system, different subsidy methods are available. Since no methane vehicle is currently present in the plant, in the analyzed case, all the bio-methane produced will be injected into the NG grid. For this choice, the subsidy is based on the MWh of energy injected to the grid (net value taking into account the system auxiliary consumption) according to the law 46/2015/R/gas. The subsidy is equal to the difference between the double of the mean yearly NG price in 2012 and the monthly NG price.

Furthermore, a 10% increase can be considered for plants with a hourly productivity lower than 500 Sm3/h and a 50% increase can be also added for plants where biogas is produced from sub-products (DM 06/07/2012 [21]).

The methodology for the investment evaluation is the calculation of the cash flow and the PayBack Time (PBT) of the investment. The complete methodology can be found in an author's previous work [20].

5. Results

5.1. Validation of biogas yield

From the results obtained (Table 4) it is possible to note that final results are very close each other. Furthermore, the value obtained is lower than the biogas hourly production declared by the farmer. However, this slight difference can be accepted considering that calculations performed with literature data are not able to exactly reproduce the complicated process of the anaerobic digestion. Then, the analyses of the following sub-sections have been carried on considering the value of 33 Nm^3/h.

Table 4. Comparison of the biogas yields found the theoretical method and declared production.

	From calculation	Plant owner declaration
Biogas hourly production (Nm^3/h)	31.3	33

5.2. Economic analysis

Performances for the three analyzed business scenarios are available on Figure 4. As can be seen, the lowest PBT is related to the ICE, with an investment recovery in less than 2 years. Then, the SOFC at lower cost can be found, which investment is repaid in 3.5 years. The biogas upgrading investment PBT is indeed 15 years and the higher cost SOFC more than 7 years. The ICE seems to be the more convenient investment, even if two considerations should be performed: first, the real plant performance have been detected to be much lower than the ideal one from the producer, for what concerning both efficiency and costs.

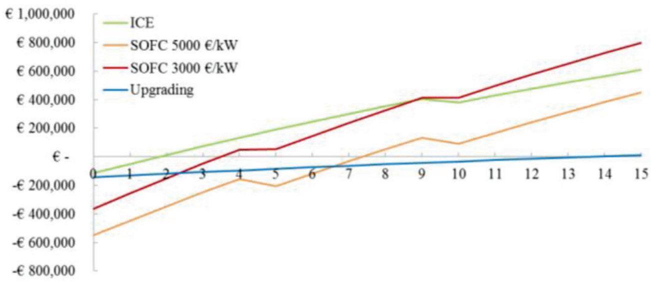

Figure 4. Economic performance of business scenarios.

Unfortunately the analysis of the current scenario was not possible due to lack of data in the current layout (no data

logging, no performance evaluation, etc). The second point related to the ICE is that nowadays, more and more similar plants require a post-combustion system to have emissions in line with regional laws (especially restricted in the Torino area). This component, if required, would strongly increase the capital cost.
The biogas upgrading system shows one of the lowest investment cost but a slow money recovery. In the presented analysis, anyway, no commercial data was available for the system considered and literature data have been used and because of the very low flow rate of biogas treated, specific cost functions result in high investment and operating costs. Furthermore, the digester thermal load has been considered as constant throughout all the year (since no data was available from the real plant) despite in summer months the contribution should be reduced because of the higher external temperature. Because of all the above-mentioned reasons, the economic feasibility of biogas upgrading in the current market scenario could lead to different results than those presented from the authors.

6. Conclusions

The presented analysis has pointed out main strengths and criticalities of the currently available biogas exploitation paths: from traditional CHP system with ICE, to high efficiency and clean SOFC CHP systems, to biogas upgrading. Both CHP scenarios have the potential to be interesting investments for the system: the choice depends on the site characteristic (electricity and NG cost, energy internal requirements, etc.) and on the availability of subsidies for the chosen scenario. For biogas upgrading, even if results seems discouraging, deeper analysis with real system costs should be performed; furthermore, the use for transportation is admitted with a different supporting scheme and this could lead to better results. All the proposed configurations, anyway, lead to a circular economy scenario where energy is produced from wastes and re-used. Future works will be related to the analysis of different business scenarios for what concerning plant size, energy costs and supporting schemes.

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